Towards the smallest anisotropic structures by ultrafast laser writing in silica glass

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Abstract: A localized nanoplane modification was created in silica glass with a few femtosecond laser pulses. Fast writing of anisotropic structures and high-density data storage can be achieved.

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1. Introduction

Femtosecond laser induced birefringent structures in silica glass have enabled space-variant polarization converters, geometric phase elements and 5D optical data storage [1-2]. So far, two types of birefringent structures have been reported; one is nanograting structures (type 2) and another one is elongated nanopores with random distribution (type X) [3]. The generation of these structures requires irradiation with dozens of fs laser pulses, which poses obstacles for fast throughput. In addition, it is difficult to fabricate nanograting or nanopore structures confined in a small volume, which prevents writing of birefringent structures with high spatial density.

Here, we report a new kind of fs laser induced birefringent modification, which is a highly localized single nanoplane. We used a pulse energy modulation (PEM) method to create the anisotropic structures. In the PEM method, pulse trains with different pulse energies are focused inside silica glass. It was demonstrated that birefringence can be created with a few pulses when the first two pulses are stronger than the succeeding pulses. Scanning electronic microscope (SEM) images revealed a circular shaped void at the center of the photoexcited region which could be transformed into single localized nanoplane. The lateral length of the nanoplane structure is about 300 nm and is smaller than 4 μm along the laser propagation direction. The size of this modification is considerably smaller than the conventional birefringent structures, such as nanogratings or a set of elongated nanopores.

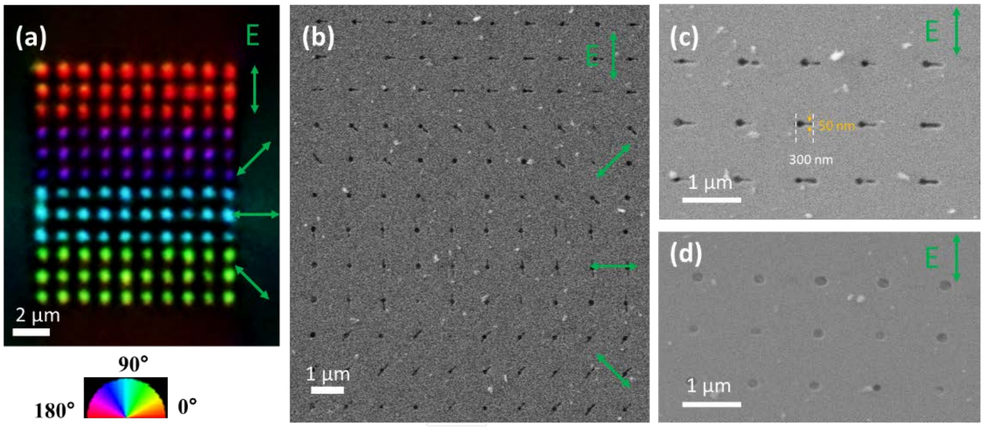

Fig. 1. Birefringent voxels written inside silica glass with a PEM method. (a) Observed slow axis orientation of written birefringent voxels. The color represents the orientation of the slow axis. (b) The SEM image of the birefringent voxels after exposing the structures on the surface by polishing. (c) Enlarged image of (b). (d) The SEM image of voxels created with two seeding pulses.

2. Results and discussion

A mode-locked Yb:KGW regenerative amplifier (PHAROS, Light Conversion) was employed as light source operating at a wavelength of 515 nm, a repetition rate of 500 kHz and a pulse duration of 300 fs. Laser pulses were focused 170 μm beneath the surface of a silica glass substrate (Corning 7980 HPFS), which was placed on an XYZ translation stage. The polarization of the laser pulses was controlled with a Pockels cell and a quarter waveplate.

The matrix of voxels was written in silica glass by focusing an fs laser pulse trains with modulated pulse energies (PEM method) with a 0.60 NA objective lens. The pulse train consisted of 2 stronger pulses (36 nJ) followed by 8 weaker pulses (19 nJ). Here, we call the first two pulse "seeding pulses" and the following pulses "writing pulses". Birefringence imaging of the voxels revealed the generation of anisotropic structures at the region where pulse trains had been focused [Fig. 1(a)]. The slow axis of the birefringence was perpendicular to the laser polarization and the average retardance was 3.1 ± 0.4 nm. The SEM image of the birefringent voxels after polishing reveals that a localized nanoplane had been produced in the birefringent region [Fig. 1(b)]. The orientation of the nanoplane was always perpendicular to the polarization direction of writing laser pulses, indicating that the nanoplane should be responsible for the birefringence. The enlarged SEM image [Fig.1(c)] shows a nanovoid at the center and nanoplane elongating from the nanovoid. The length and width of the nanoplane are shorter than 300 nm and 50 nm, respectively [Fig. 1(c)]. The structures created by seeding pulses is a circular shape nanovoid with a diameter of 200 nm [Fig. 1(d)], suggesting that the nanovoid is a seed for the subsequent formation of the localized nanoplane.

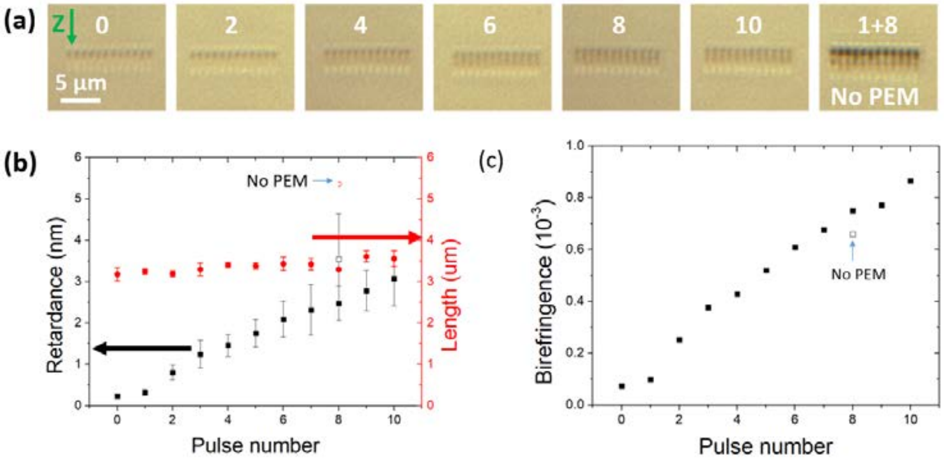

Fig. 2. (a) Optical microscope images of structures generated with different writing pulse numbers, which were observed perpendicular to the laser propagation direction (Side view). (b) Measured retardance and the longitudinal length of the modifications in (a). (c) Calculated birefringence of structures in (a).

The optical microscope image of the structures along the beam propagation direction [Fig. 2(a)] shows that the modified region consists of a dark head and a bright tail. From the phase measurement of the structure, the dark and bright regions have negative and positive refractive index changes, which demonstrates that a localized nanoplane was created in the dark head and densification occurred in the bright tail. The retardance of the birefringent structures by PEM growths with increasing writing pulse number, while there was a small increase in the length of the structure. The length of the structure is as short as 3.5 μm, which is 1.5 times smaller than that without PEM. The maximum birefringence was about 0.9×10^{-3} [Fig. 2(c)], which is smaller than the typical birefringence (3×10^{-3}) of femtosecond laser induced nanogratings (type 2) but enough large to detect them.

3. Conclusion

In conclusion, we demonstrated the recorded high localization of nanoplane birefringent modification in the volume of silica glass by a few fs pulses laser direct writing. If the length of the nanoplane can be controlled at two levels and the orientation can be modified with an accuracy of 1 degree, 8 bits data [2 levels for retardance (1 bit) and 128 levels for azimuth (7 bits)] can be record at one voxel. According to the lateral and longitudinal lengths of the localized nanoplane (potentially 0.2 μm and 3 μm, respectively), the possible data capacity of a 125 mm ×125 mm × 3 mm glass plate is 380 TB. This breakthrough could enable remarkably stable data storage media with a high data capacity.

References

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